Future Treatment of Weld Acceptance:

The Significance of Incomplete Fusion Discontinuities in Low Structural Transition Temperature GMAW Weldments

by

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Abstract

The welding acceptance standards for naval ships and submarine pressure hulls indicates that the presence of any incomplete fusion discontinuities in the welds is cause for rejection. In this paper, it is suggested, depending upon the size and location of the discontinuity and the weldment structural transition performance, that certain amounts of incomplete fusion are acceptable. In short, weldmetal tearing resistance, often overrides the weld discontinuity's influence on weldment failure.

In our study, six explosion bulge panels were welded to have severe incomplete fusion flaws in weldments which otherwise exhibited low structural transition temperature performance; two panels had root flaws and the other four had cap flaws. Explosion bulge tests were performed to determine if the welds could resist crack extension beyond the limits of the bulge apex.

Prior to explosion testing, the welds were examined with manual ultrasonics and computer-aided ultrasonics. They were also radiographed at plus and minus twenty degrees to normal (standard radiography would be shot at normal). The NDT was conducted to relate performance back to NDT (as opposed to just discontinuity size, nature, and location).

Following explosion testing, the welds were sectioned and opened to determine the true discontinuity nature and size, and the degree and nature of extension under explosive loading. Sectioning showed that extension was always by a ductile mechanism for these low structural transition weldments.

Based on this work, discontinuity size and location was found to be less of a determining factor in the quality of the weld than the structural transition performance of the weld and steel. It was found that acceptance criteria should be based on whether the structural transition performance is below, within or above the operational envelope, as well as, and not just on the size and location of discontinuities.

INTRODUCTION

Traditional welding practices and non-destructive acceptance standards are obstacles to the full engineering exploitation of the combination of advanced welding methods (eg. pulsed gas metal arc welding with standard, tertiary and quaternary shielding gases with heat inputs below 1kJ/mm [1,2]) and high toughness structural steels (as a minimum, steels higher than grade E). As such, they are also an obstacle to the production of the best and safest product at the best price. To overcome the obstacles which these practices and standards present requires that we consider their historical and scientific basis, and the engineering institutions which have resulted. Also, the limitations of these standards must be identified and the work required to extend them to the case of advanced welding methods and higher toughness structural steels must be defined.

Implicit in todays standards is a fear of brittle fracture. History shows that this fear is justified. Brittle fracture requires a defect, a load and a steel (or weldment) at a temperature below its structural transition temperature (structural transition [3] is the true transition of the structure as opposed to the fracture transition of a particular specimen: note that this is much different than the charpy transition). There are reports of weld defects an inch long acting as the initiation site in the catastrophic failure of a ship [4]. The weld defects act as initiation sites for brittle fracture directly or indirectly by the initiation of a fatigue crack. It is concern for these defects which inspires acceptance rejection/criteria standards. The history of how the limits for porosity, slag and incomplete fusion defects came about is 'lost in the fog of engineering history'. (Weck [5] went so far as to suggest that the acceptance criteria were perhaps a result of divine intervention.) Tradition has it however, that our naval standards were adapted from ASME standards developed in the late 1940s. Tradition also has it that the 1940s ASME standards were not developed from consideration of structural performance in the presence of defects but from agreement on the amount of rework that would be tolerable. They balanced quality with cost to determine acceptance levels. In later years as fracture mechanics grew the existing acceptance standards were often rigorously evaluated against the developing fracture mechanics technology and survived this close scrutiny. The acceptance standards survived because the situations evaluated typically involved small defects that were tested near the structural transition temperature.

What has been missing in the design of weld acceptance criteria was a complete overview of weld acceptance from a combined NDE, fracture and welding perspective. In this paper we present the results of a study which combines severe incomplete fusion discontinuities, advanced NDE evaluations, explosive testing and detailed metallurgical characterization. Six explosion

bulge test panels (TM-1 through TM-6) were welded to have incomplete fusion flaws; two panels had root flaws (TM-1 and TM-4) and the other four had cap flaws. These flaws were non-destructively examined using radiographic and ultrasonic methods (manual and computer-aided) before the explosion bulge testing.

The explosion bulge tests were performed to determine if the welds could resist crack propagation beyond the limits of the bulge apex at minimum design test temperatures. Normally, plates are explosively loaded to cause a strain of 16%. For our experiments, tests were halted when the defects broke to the surface if at least ten percent strain had already occurred, to permit more detailed fractographic examination. If, upon reaching 16% strain, the crack in the weld had not extended beyond the bulge apex, the amount of incomplete fusion discontinuities would be considered tolerable. Using these results a comparison was made based on initial discontinuity size and location (i.e. root or cap), discontinuity extension, and the ultrasonic reflectivity level.

The results showed that depending on the size and location of these discontinuities that with a favorable weldment structural transition performance, that certain amounts of incomplete fusion are tolerable. This report further suggests that rather than being concerned with crack initiation in the weld, it may be better to examine the resistance of that weldment to crack extension.

BACKGROUND

To consider the three disciplines simultaneously when examining weld acceptance one must consider discontinuities and structural transition performance together, not just discontinuities. The steels and weldments which were principally considered at the inception of these standards were (and in large part still are) materials which have a structural transition temperature above the minimum operational temperature of the component at question. Many welding practitioners operate on the assumption that discontinuity free welds are the goal. This is not really the case. Techniques which tend to control or eliminate weld discontinuities such as higher heat input tend also to be detrimental to the structural transition performance. For example, our experience is that grade A to D steels, and standard industrial SMAW (shielded metal arc welds) have their structural transition mid points near 0°C. Consequently todays rigorous weld acceptance standards, by default, become necessary for these material combinations. (But in reality, this provides an imperfect sense of security).

Today there are a number of families of steels (i.e. above grade E) and advanced welding processes which allow the cost effective fabrication of components which have a structural

transition temperature below the operational envelope of the component. Application of standard acceptance criteria here is inappropriate (unnecessarily conservative) in our view and raises significant questions.

The questions which need to be addressed are:

1) Are these restrictive weld acceptance criteria (the standard acceptance criteria) appropriate for a class of weldments which is clearly different (having improved structural transition) than those used in most of the evolution of the criteria.

2) When the standard acceptance criteria are applied to materials with low (improved) structural transition, do they enhance or degrade the final product.

3) Does applying standard acceptance criteria add unnecessarily to the cost of structures fabricated from these materials with lower transition, making them less cost effective without a good scientific reason; and

4) Do the traditions/assumption and myths which have evolved with the traditions of standards interfere with the sensible introduction of high toughness weldments (low structural transition weldments).

It is well known that gas metal arc weld (GMAW) techniques are prone to incomplete fusion defects. This has been the most important factor impeding their wide adoption as alternatives to SMAW [6]. This is true even though they offer improved structural transition performance and, as a low hydrogen process, a reduced tendency to hydrogen cracking, which is more severe than incomplete fusion and often surface breaking. In our experience, the problem of acceptance of such welding techniques is more complicated than just the observation that for some applications and welds it fails the existing incomplete fusion acceptance standard too often. There is also a perception that the pulsed GMAW is worse because it induces a higher number of incomplete fusion indications which are acceptable by current standards. With such GMAW methods, it is possible to reduce incomplete fusion discontinuities by increasing heat input. This degrades the structural transition and takes away from its inherent advantage. It is our supposition that a different acceptance criteria is required for a weld which has a structural transition below its intended operational envelope than when the structural transition is within its operational envelope (the latter being inherently risky while the former is not).

In summary, what is required is a unified approach which incorporates in the weld acceptance and welding standards the perspectives of NDE, fracture mechanics and welding. It is our view, that an important step towards more rational and unified welding and NDE standards and also towards the more widespread use of gas metal arc welding in place of SMAW are convincing demonstrations:

1. that lack of fusion defects can be found reliably and assessed accurately by a variety of NDE techniques; and
2. that for a material with a structural transition below the operational envelope the sorts of incomplete fusion defects a welder might make without knowledge, both above and below the defect rejection level, when severely loaded will extend only in a ductile manner and not cause structural failure.

As indicated in the introduction, the required demonstrations were carried out by: producing controlled incomplete fusion discontinuities in high toughness pulsed gas metal arc welding in HY100 plates; characterizing these discontinuities non destructively with enhanced radiography, manual ultrasonic and computer aided ultrasonics; loading these incomplete fusion containing plates with explosion bulge tests (which simulate severe structural performance) and characterizing the discontinuities and their propagation by sectioning and metallography after the explosion bulge test. The purpose of the metallography is both to assess the limits of the various inspection techniques for incomplete fusion and more importantly, to assess the amount and type of crack extension which occurred during testing. In the remainder of this paper, we give relevant background on the main parts of the experimental program, the welding methods, the controlled introduction of incomplete fusion, the inspection methods, the explosion test method, metallurgical characterization of the discontinuities, comparison of the discontinuity detection abilities of each NDE technique, and a discussion of our acceptance criteria analysis.

WELDED TEST PLATES (TM-1 to TM-6)

The project began with the generation of low structural transition weldments (i.e. structural transition below -20°C) containing controlled amounts of incomplete fusion discontinuities. Each panel consisted of two HY 100 steel plates welded together. Each plate was 25 mm thick and contained a double V-groove weld with 60 degree included angles and a root face of 0 mm. The weld groove was oriented perpendicular to the rolling direction [7]. The welds were made to have controlled incomplete fusion flaws; two panels had root flaws and the other four had cap flaws.

The root flaws had interpass or side wall incomplete fusion in the root region, and the cap flaws similarly had an interpass or side wall incomplete fusion in the cap passes.

Welding

Electric resistance heating was used to preheat the welds. (This is essential in viable weld procedure studies). An electronic chart recorder coupled with a 6 zone mini-controller and a 75 kW transformer were connected to two heaters and two K-type thermocouples were spot welded to the panels to control and record the temperature. Interpass and preheat temperatures were monitored and welding was delayed until interpass temperatures were reduced to acceptable values (i.e. below 150°C). After welding was complete, the panels were wrapped in insulation and allowed to cool to room temperature. Welding procedures were prepared and the influence of parameter changes was investigated using the 120S-1 weld wire. The parameters giving the most desirable effects were then used to create the discontinuities [7].

Backgrinding to sound metal of the root prior to welding Side 2 was conducted on all panels. Electrical grounding of the workpiece was accomplished by clamping the ground cable in the line of the weld groove. In all cases the welding progression was towards the ground. In depth details of the welding procedure used may be obtained in Appendix A of reference 7.

With exception of the discontinuity introduction, the highest quality welding was employed to produce the weldment. This guaranteed that the weldment would exhibit high quality structural transition away from the discontinuities. This is contrary to studies in which the total weld procedure was degraded to produce discontinuities. In those cases physical tests did not evaluate the role of the induced discontinuities but measured the degradation of the total weldment. In our experiments care was taken to ensure high quality welding (good/low structural transition performance) with discontinuities present as the test condition.

Incomplete Fusion Discontinuities

Most GMAW processes are especially prone to incomplete fusion discontinuities. Their presence is greatly influenced by the composition of the shielding gas. The TIME Process [1], a modification of GMAW, was engineered to reduce incomplete fusion. The TIME shielding gas generates intense heat in the arc and is considered to be much more reliable in eliminating fusion discontinuities than other gas mixes. However, in joining high strength materials such as HY 100,

the application of low heat inputs needed to achieve high notch toughness can still give rise to the incidence of incomplete fusion.

In multi pass butt welds, the middle third of the plate is the region where incomplete fusion discontinuities are most likely to be implanted without the operator's knowledge.

Incomplete fusion may be caused by:

incorrect electrode position
weld metal running ahead of the arc
dirty steel
filler metal characteristics
welding procedure (e.g. insufficient current, too long an arc, improper joint design, insufficient heat input)

Root incomplete fusion discontinuities are very sensitive to increases in arc voltage (PV) due to the constriction of the joint. The root discontinuities in plates TM-1 and TM-4 were created by increasing PV from -3.5 to +3.0, an increase in arc voltage of approximately 6 volts.

Cap pass discontinuities are difficult to produce and are unlikely to occur in fabrication with qualified operators. The conditions required for such discontinuities to occur would be noticed during normal welding operations. The conditions used to produce the cap pass discontinuities are detailed in reference 7.

Root pass discontinuities were introduced only on Side 2. Cap pass discontinuities were implanted on the final layers of both Side 1 and Side 2. UT was used to determine the most suitable side for further evaluation and was subsequently ground smooth for explosion bulge testing.

NON-DESTRUCTIVE TESTING

Before the explosion bulge testing, the flaws were non-destructively examined at DREA using manual ultrasonic inspection, computer-aided ultrasonic inspection (using APHIUS, the Automated Pressure Hull Intelligent Ultrasonic System [8]) and enhanced radiographic methods.

Manual Ultrasonics

Ultrasonic inspection was employed to characterize and measure the depth of discontinuities. The UT was performed using a Sonic MK I and an A85087 transducer with a probe angle of 70°. This probe angle has been found to be most effective in finding the incomplete fusion discontinuities in this joint configuration. The reference reflections were calibrated in accordance with ASME VIII and based upon a 3/32" diameter hole in the calibration block.

For these butt joint welds, the acceptance criteria was dependent on signal level. For a reflectivity of 12 dB or more in excess of the reference standard (a strong indication of larger flatter discontinuities such as cracks or incomplete fusion) rejection was automatic. For reflectivity greater than the reference but less than 12 dB greater than the reference, acceptance was determined when:

> the maximum length of a continuous discontinuity is less than t or 38 mm, whichever is less (t = 25 mm); discontinuities are separated by at least 1.25 times the length of the larger discontinuity; clusters of small discontinuities are assessed as a single indication; and the total length of discontinuity in any 1200 mm length of continuous weld shall not exceed 75 mm (proportional for weld lengths less than 1200 mm).

Table 1a: Manual ultrasonic test results for the 6 plates.

Plate	Flaw Type	Reflectivity	Length (mm)	Observations
TM-1	root	+100 %	50	side 2 ground
TM-2	cap	50-100 %	50	side 2 ground for testing
TM-3	cap	+100 %	50	side 2 ground for testing
TM-4	root	+100 %	100	side 1 ground
TM-5	cap	50-100 %	100	side 1 ground for testing
TM-6	cap	+100 %	100	side 1 ground for testing

Computer-Aided Ultrasonics (APHIUS)

The system used for computer-aided ultrasonic evaluation was APHIUS, the Automated Pressure Hull Intelligent Ultrasonic System [8]. It contains a high-performance ultrasonic pulser

with receiver and state of the art digitization for rapid data acquisition and processing. It provides computer assistance to an inspector in four ways:

permanently recording the discontinuity indications
mapping the location of the flaws
displaying standard ultrasonic information during the test, and
allowing the operator to review and classify the discontinuities

APHIUS produces longitudinal B-scans which show the depth of discontinuities. Transverse B-scans indicate the location of discontinuities in the weld profile. APHIUS is referred to as intelligent because it can help the operator distinguish between tolerable discontinuities and those calling for material condemnation. It was believed that this technique would provide the greatest ability to detect discontinuities.

The characteristics of the initial discontinuities as determined using the APHIUS system are shown in Table 1b below.

Table 1b: Computer-Aided Ultrasonic test results for the 6 plates.

Plate	Reflectivity	Length (mm)	Depth (mm)	Observations
TM-1	120 %	38	11	
TM-2 side 1	30-60 %	51	3.5	
TM-2 side 2	50-100 %	51	3.5	
TM-3 side 1	100-120 %	64	3.5	
TM-3 side 2	100-120 %	64	3.5	
TM-4	140 %	114	10	
TM-5 side 1	50-100 %	102	3.2	intermittent cracks
TM-5 side 2	50-100 %	127	3.2	
TM-6 side 1	50-110 %	127	2 and 3.5	
TM-6 side 2	50-100 %	127	3.5	

Discontinuity length and reflectivity results are similar to those provided by the manual ultrasonic inspection . APHIUS, however, also indicates the depth of the flaw. A printout of typical APHIUS results produced from two sides of the weld is found in Figures 1a and 1b.

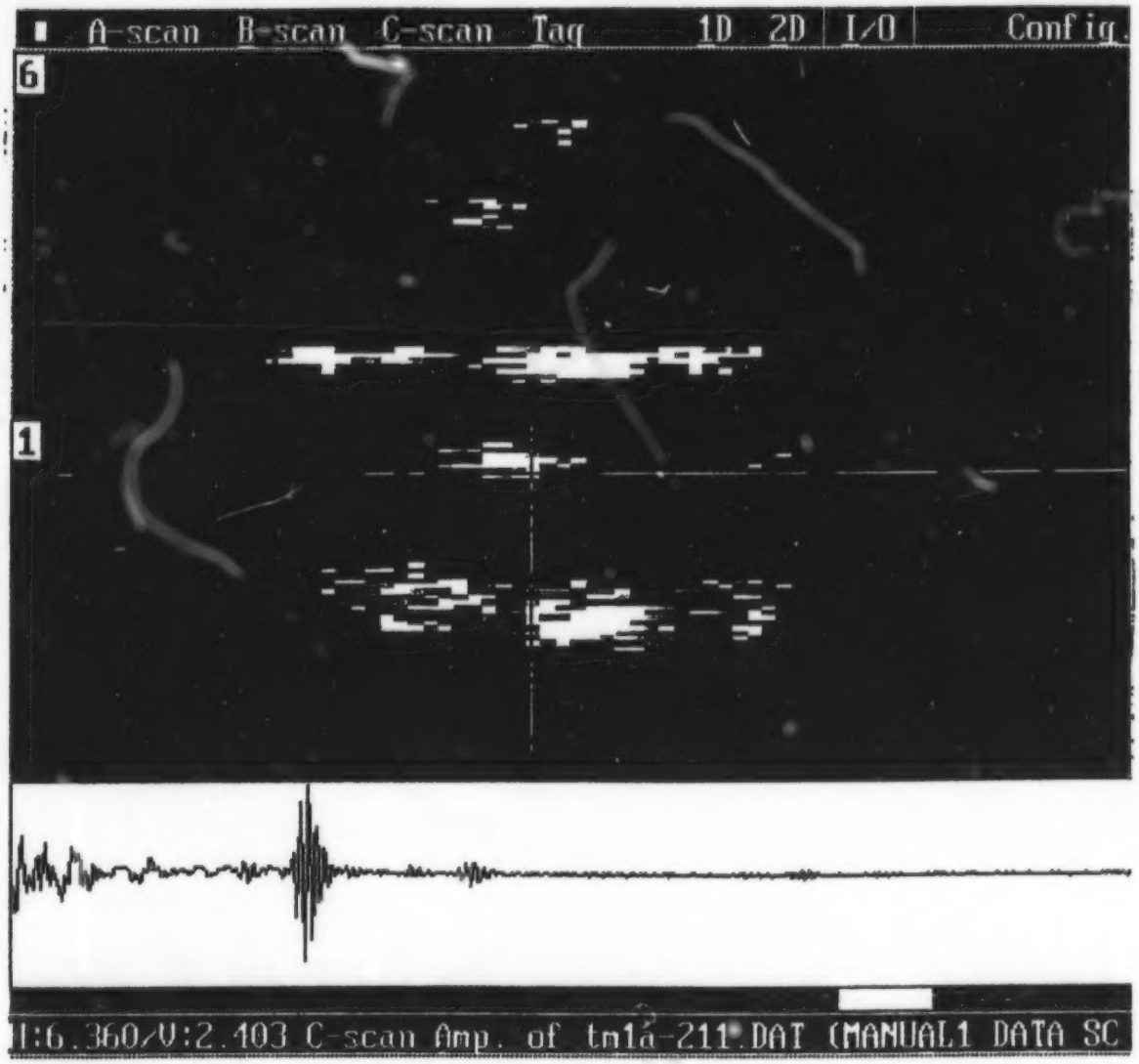

Figure 1a: Computer-aided ultrasonic scan of plate TM-1.(viewed from top)

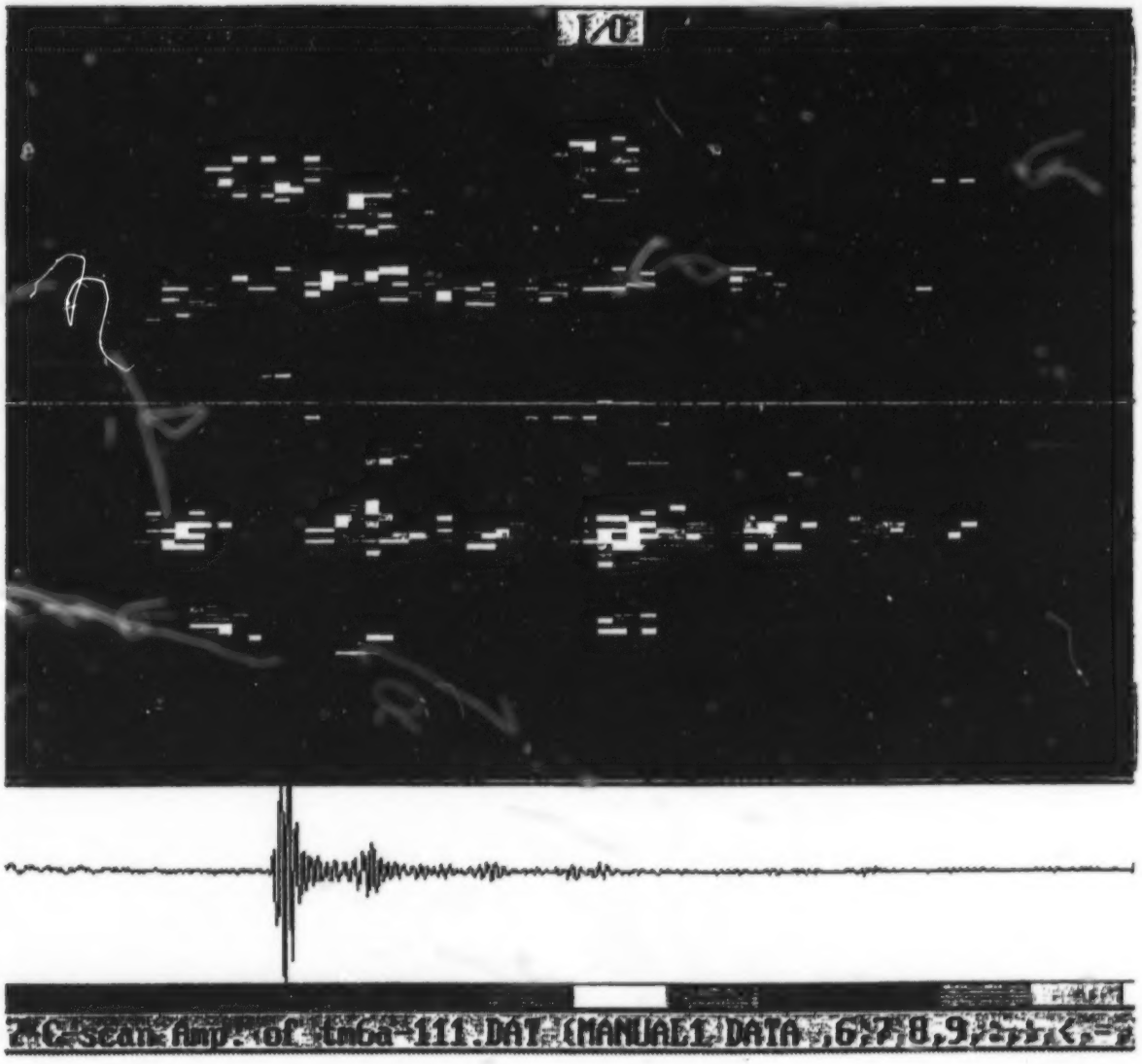

Figure 1b: Computer-aided ultrasonic scan of plate TM-6.(viewed from top)

Enhanced Radiographic Inspection

Radiographic examination was carried out using standard methods, however, to ensure greater detection results, x-rays were taken at angles plus and minus 20° from normal incidence (the normal practice is to take a single shot at 0°). This enhanced technique has a considerably higher probability of detection, over standard techniques, as the line of separation of incomplete fusion discontinuities often lies at an angle parallel to the edge preparation and is easier to detect when shot parallel to it. It is generally accepted that the single shot normal to the surface, has a probability of detection below computer aided ultrasonics, so as a secondary issue in this report we wanted to give radiography a fair chance by utilizing the two shot method. The relative cost issue aside, this study should create a fair comparison of the probability of detection of the two techniques.

Indications were considered separately if the ends of two adjacent indications were separated by a distance greater than the larger of the following:

2.25 times the thickness of the plate (25 mm)
1.25 times the length of the larger indication

On a radiograph an incomplete fusion discontinuity will appear as a very fine dark line or a line of varying width when accompanied by slag. The x-rays for typical plates are shown in Figures 2a and 2b. Table 2 provides interpretation of all the radiographs taken.

Table 2: Radiographic test results for the 6 plates. Length of indication for each shot plus length of discontinuity determined from combined interpretation of the three shots.

Plate	0° (mm)	+20° (mm)	-20° (mm)	Combined (mm)
TM-1		11	67	67
TM-2		61	65	69
TM-3		89	93	93
TM-4	22	7	112	112
TM-5		49	37	70
TM-6		83	81	84

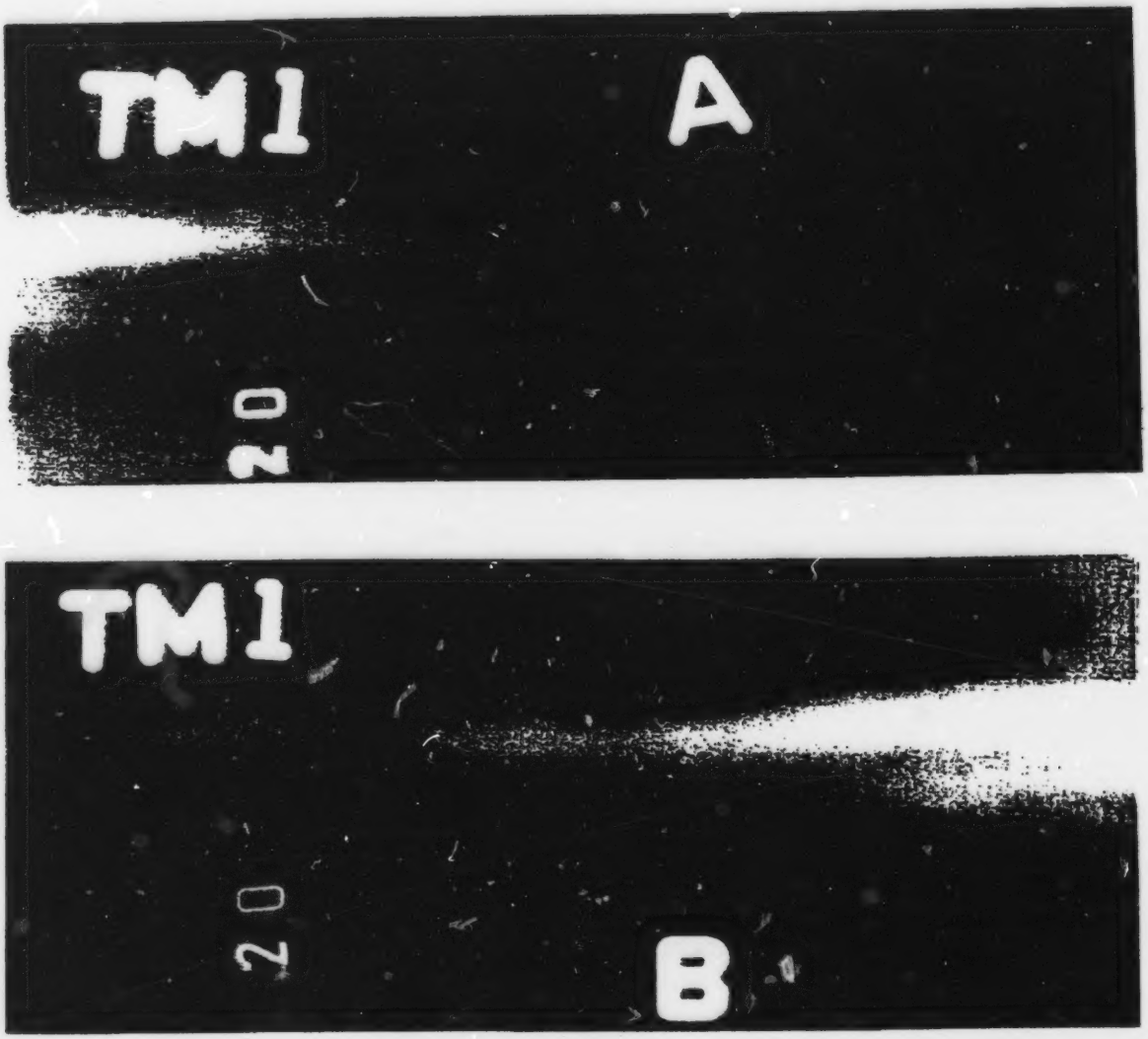

Figure 2a: Radiographs of panel TM-1 taken at $+20^{o}$ and -20^{o} to normal.

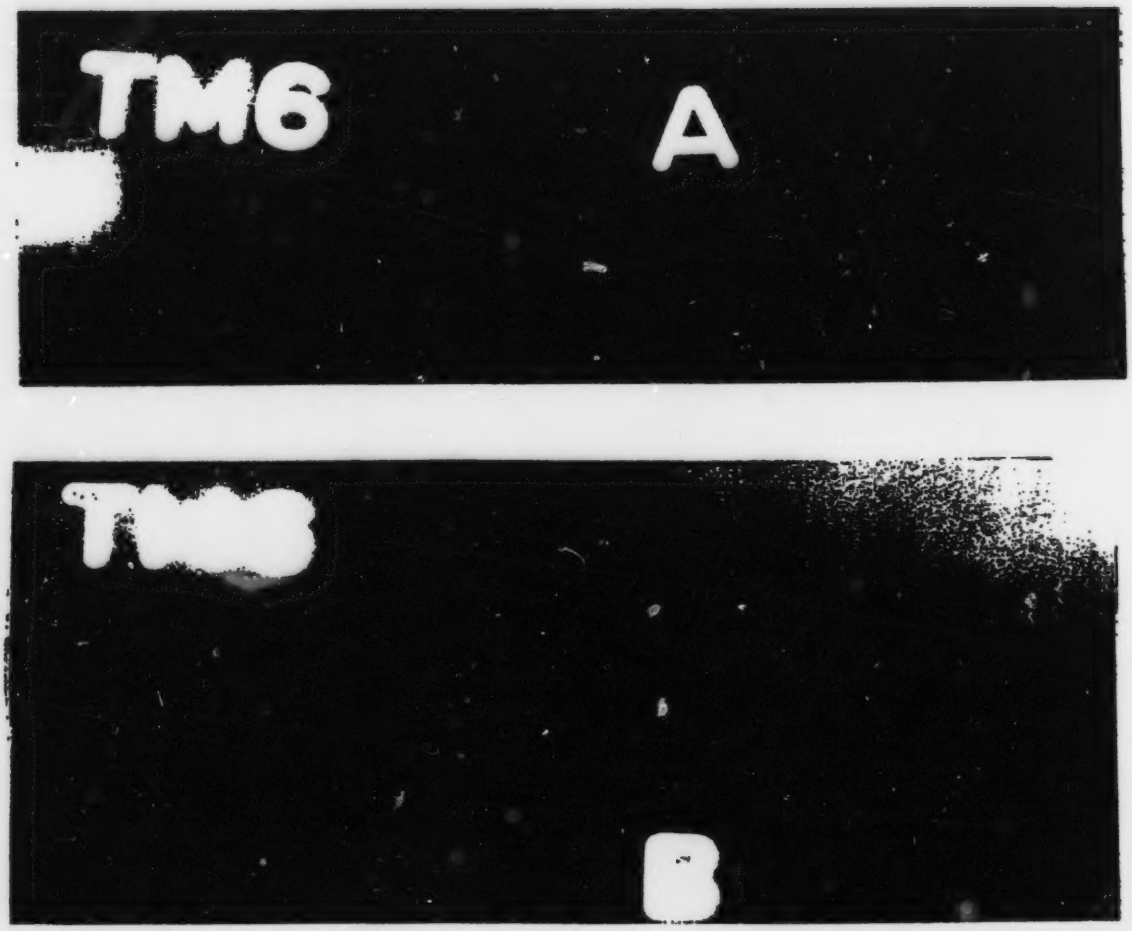

Figure 2b: Radiographs of panel TM-6 taken at +20° and -20° to normal.

By taking two shots at plus and minus 20° to normal more of the incomplete fusion discontinuity could be seen than by taking a single shot normal to the plate. At +20 we detected very little of two discontinuities and half of one of them. At -20 we detected only half of one discontinuity but the majority of the rest. Using both +20 and -20 we found all of four discontinuities and 90% of the other two. Clearly this enhanced two shot approach to radiography is technically as successful as computer-aided ultrasonics.

EXPLOSION BULGE TESTING

Following welding and NDT, the plates were explosively deformed using the DREA underwater explosion bulge procedure [9,10]. In this procedure, the 24 inch square, full thickness samples were placed on an anvil which had a 15 inch diameter circular cut-out removed, with ground surfaces contacting the die. An explosive charge was suspended over the center of the specimen, maintaining a proper stand-off distance.

The plates were cooled to a temperature below the required test temperature so that any heat gain during handling would not cause the test temperature to be exceeded. Test specimens being cooled were allowed to normalize in temperature through thickness (normally 1 hour per inch). Thermocouples were used to monitor the test plate temperature.

Prior to detonation, the entire test assembly was submerged in a water filled pit. The water acts as an efficient explosive energy transfer medium between the charge and test piece thus reducing the weight of explosives to affect the required deformation. When the test piece attained the proper temperature, the charge was detonated creating a uniform gas pressure which clamped the test piece to the anvil. The pressure wave deformed the test plate material into the anvil opening, developing a balanced biaxial plastic set strain field in the bulge apex region of the test piece.

The clamping effect of the plate to the anvil is important to the efficient generation of the bulge apex strain levels. Loss of this clamping would delay the transition of the bending wave deformation action to the membrane stretching biaxial elongation. Sufficient stand-off distance is required to eliminate the impulse loading effects generated by contact charges.

After each shot, the specimens were examined, and the location, length and direction of all cracks recorded. Through thickness thickness changes, which are proportional to surface strain

levels, were measured and recorded. Before each successive explosive loading, the test specimens were returned to the cooling medium long enough to thermally recondition them.

Explosion Bulge Results

The explosion bulge tests caused the initial incomplete fusion flaws to propagate. The root flaws propagated through the thickness of the plate whereas the cap flaws only extended by small amounts on the convex side, in all cases propagating to that surface. The cap flaws on the concave side did not propagate. The mechanism of flaw propagation was identified as ductile.

Measurements were taken of both the initial and final flaw lengths and depths. Photographs displaying the typical appearance of the final flaws emerging on the convex surface of the test panels may be observed in Figures 3a and 3b.

Table 3: Charge weights and stand-off distances used during underwater explosive bulge testing for plates TM-1to TM-6 and results of each loading.

Plate	Shot	Stand-off (in.)	Charge Weight (lbs)	Strain (%)	Length and Observations
TM-1	1	6	8	8.5	no tears
	2	6	8	17.3	through thickness fracture
TM-2	1	6	4	11.4	short tears, tensile side (~2 in.)
TM-3	1	6	4	10.3	2.5 in. shallow tears (tensile side)
TM-4	1	6	6	7.4	no tears
	2	6	6	16.7	through thickness crack
TM-5	1	6	5.25	13.0	2 inch tear (tensile surface)
TM-6	1	6	8	14.4	

The cap flawed specimens were deformed less than the root flawed specimens because the initial charge broke the surface of the cap flawed specimens and these tests were ended. The root flawed specimens were deformed by a second shot until the discontinuities broke the surface.

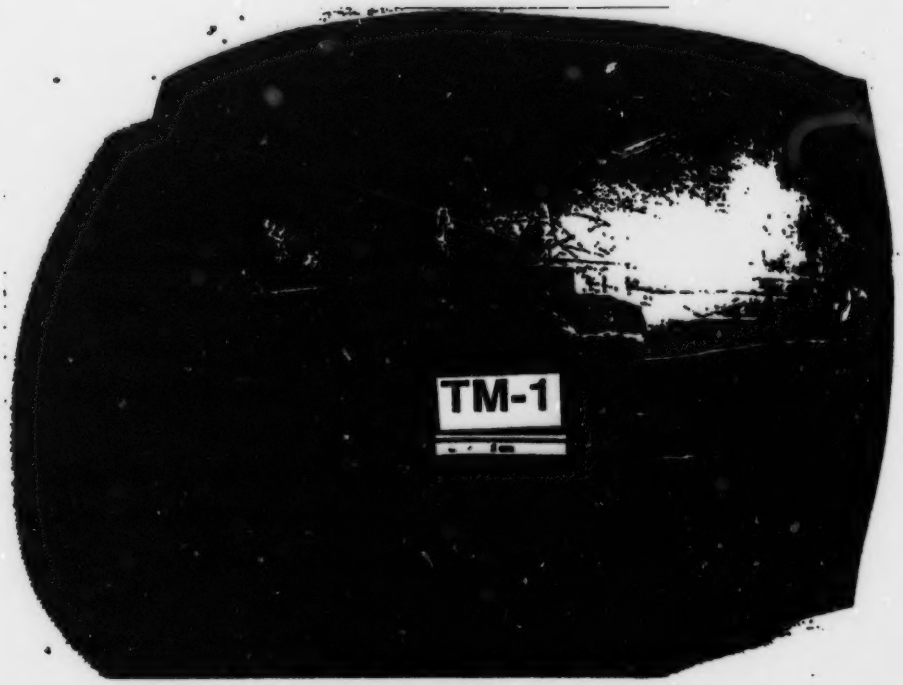

Figure 3a: Panel TM-1 contained root flaws (yellow marks indicate the initial flaw length determined by UT)

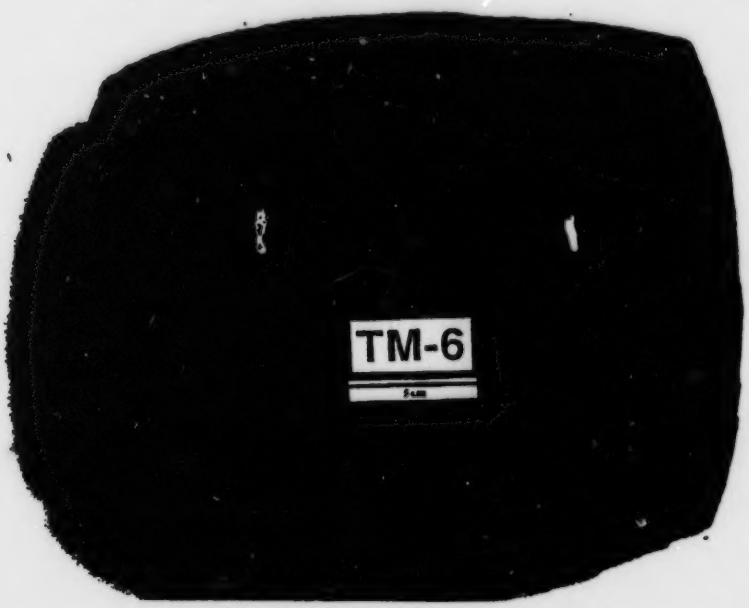

Figure 3b: Panel TM-6 contained cap flaws. (yellow marks indicate the initial flaw length determined by UT)

METALLURGICAL CHARACTERIZATION

The deformed explosion bulge panels were broken open at the weld by immersing in liquid nitrogen and employing a three point bending arrangement [11]. The objective was to expose both the initial flaws resulting from incomplete fusion, and those that propagated as a result of the explosion bulge test.

The test panels were first reduced in size by removing the excess length of weld so that the total remaining weld length extended 12-15 mm beyond the extremes of the flaw emerging at the convex surface or the UT based initial flaw length, whichever was greater. The entire remaining weld length was then immersed in liquid nitrogen and subjected to a three point bend with the convex surface taking the tensile load. This method of fracturing the test panels resulted in exposing both sides of the flaw for most of its entire length. One side was selected for display and the other was used for the extraction of specimens for stereoscopic examination, scanning electron microscopy (SEM), and cross sectional metallography.

Fracture Surface Inspection

After cleaning to remove surface rust, the fractures were examined visually and selected areas were examined under the stereoscope at magnifications of 10 to 30X. The length, location with respect to thickness, and mean depth of the initial flaws were measured on the exposed fracture surfaces. These measurements were compared with those made earlier using ultrasonic inspection and enhanced radiography.

Figure 4a indicates a typical fracture resulting from the presence of root flaws. The thinner arrows indicate the length of the initial flaw while the thicker arrows show the extent of the final flaw. Figure 4b is typical of a panel containing cap flaws where explosion bulge testing resulted in propagation of the near surface flaws to the convex side. The initial flaw on the concave side is visible and it is clear that they did not propagate during testing. Compared to the through-thickness flaw propagation in panel TM-4, the cap pass discontinuities displayed a relatively small extension during explosion bulge testing because they were subjected to fewer shots and thus less deformation.

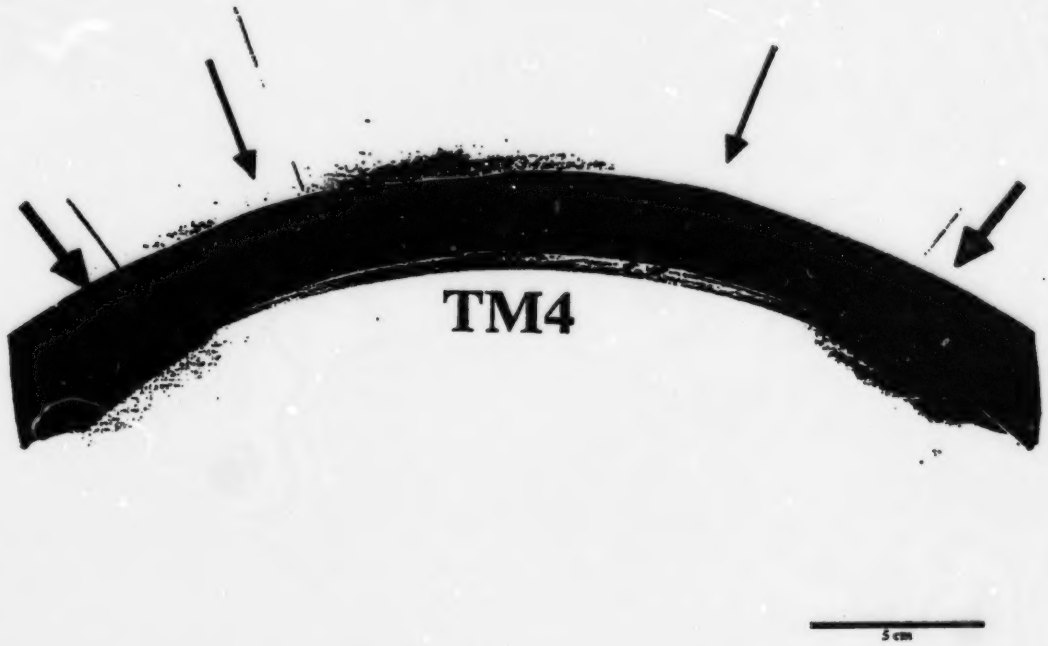

Figure 4a: Fracture surface of panel TM-4 containing root flaws. The arrows indicate extremes of initial and final flaws.

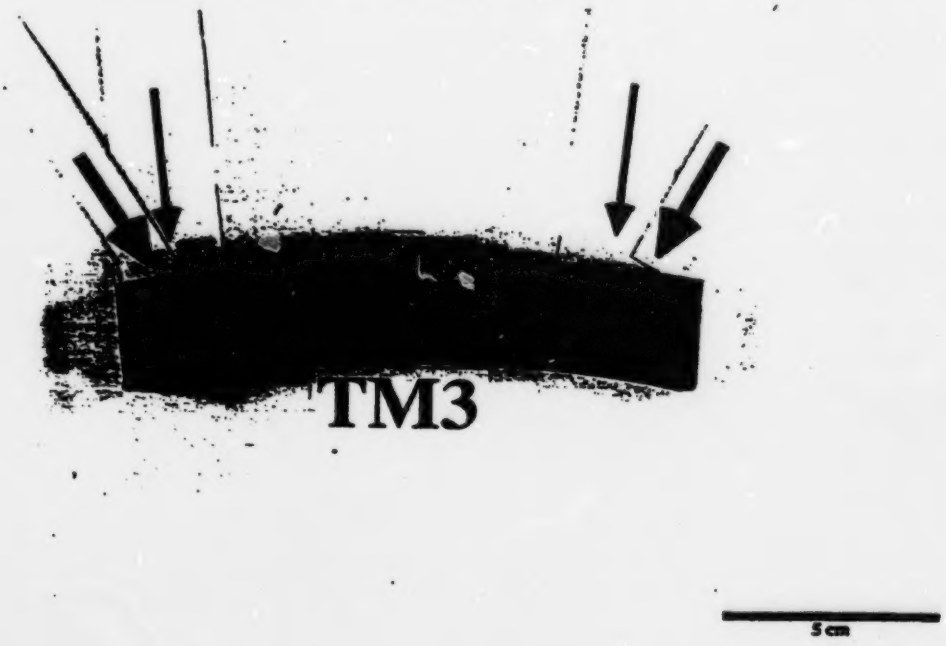

Figure 4b: Fracture surface of panel TM-3 containing cap flaws. The arrows indicate extremes of initial and final flaws on the convex side.

Table 4 indicates the lengths, approximate location in relation to the nearest surface, and the depths of the initial flaws as observed on the fracture surfaces. Figures 5a and 5b show schematics of these results.

Scanning electron microscopic examinations of each panel in numerous locations confirmed that the initial flaw surface was relatively featureless (see Figure 6a) while propagation of the flaw resulting from the explosion bulge testing occurred by the ductile fracture mechanism, as indicated by microvoids (Figure 6b).

Table 4: Fracture surface inspection results of initial flaw size and location for the 6 plates.

Plate	Flaw Type	Length (mm)	Depth+ (mm)	Location (mm)
TM-1	root	68 *	1.5-5.0	10
TM-2	cap, side 1	65 *	0.5-3.5	2.5
TM-2	cap, side 2	54 *		2.5
TM-3	cap, side 1	90 *	0.5-3.0	4
TM-3	cap, side 2	81 *		4
TM-4	root	117	1.5-5.0	10
TM-5	cap, side 1	91 *		2.7
TM-5	cap, side 2	59 *	0.5-1.5	2
TM-6	cap, side 1	76 *		2.3
TM-6	cap, side2	106 *	1.0-4.0	2.3

* not continuous

+ depth range was measured in the flaw close to the convex surface only

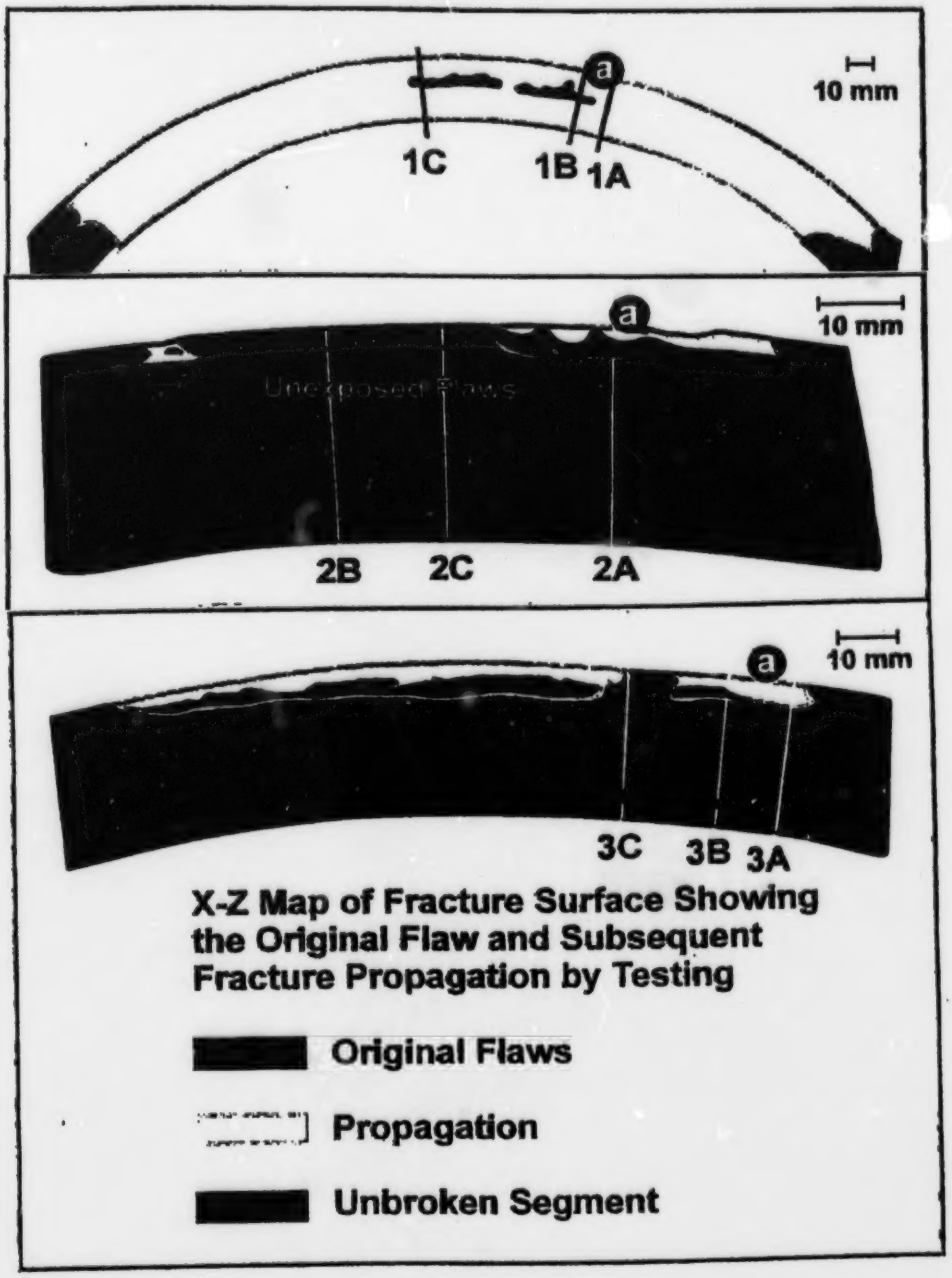

Figure 5a: X-Z maps for panels TM-1, TM-2 and TM-3.

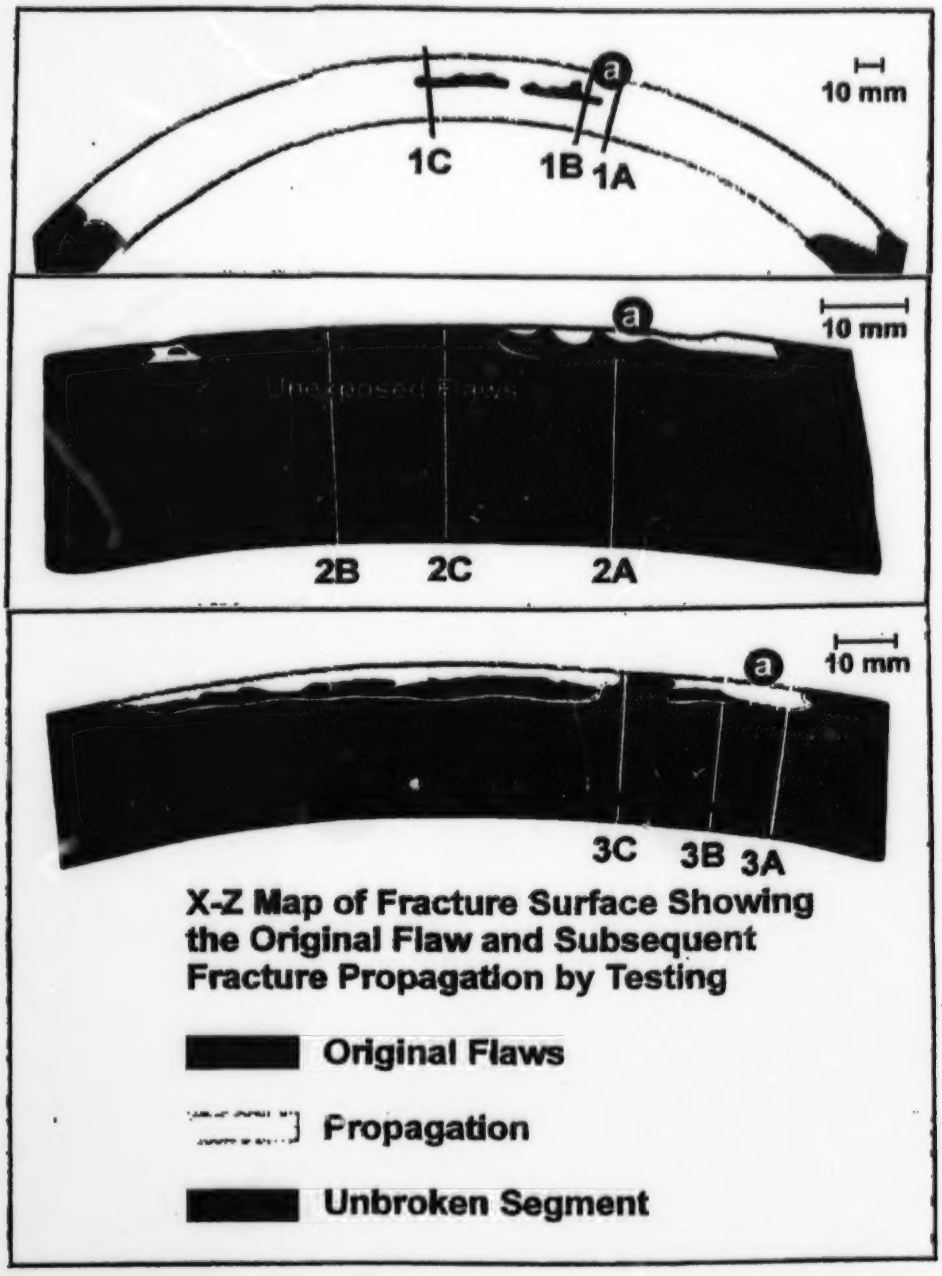

Figure 5a: X-Z maps for panels TM-1, TM-2 and TM-3.

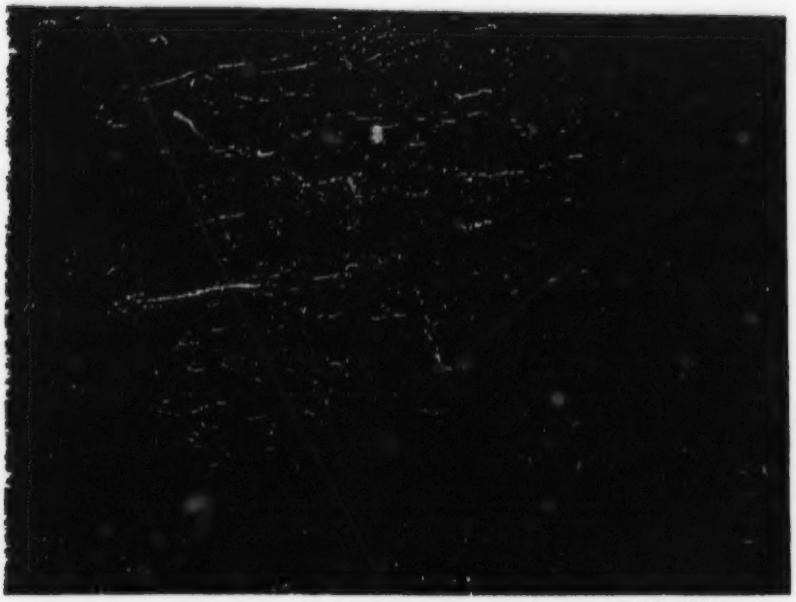

Figure 6a: SEM view of the typical appearance of the initial flaw area (TM-4).

Figure 6b: SEM fractograph of typical explosively torn area displaying propagation by microvoids.

Cross-Sectional Metallography

At select locations, some from regions containing the initial flaw and some from outside these regions, through thickness cross-sections were extracted to confirm initial flaw locations and determine flaw propagation with respect to the weld microstructure.

Observations made on the cross sections of a typical weld with root flaws, plate TM-4, indicated that the initial flaw, delineated in the fracture face with a featureless appearance, is indeed at the weld root and propagation of the flaw through the thickness occurred in the heat affected zone (HAZ) or in the base metal. Outside the initial flaw area but in a region where propagation occurred through the thickness the propagation was in the weld metal. Thus, in general, propagation of the flaw took place in the weld metal, in the HAZ, or in the base metal, depending on location. (This indicates that resistance to propagation was similar in all zones...there was not an easy path for the crack to advance with low energy release).

The cross-sectional metallographs of panels with cap flaws indicated that the initial flaws, delineated in the fracture face with a featureless appearance, were indeed in the cap passes of the weld and that the propagation occurred in the weld metal on both sides of the initial flaw in the radial direction. These fractures did not expose a continuous initial flaw on the fracture surfaces (see Table 4). Cross-sections were therefore extracted in all of these fractures at positions that do not show the propagation of the flaw. Using these an attempt was made to establish if the flaw was indeed continuous on the convex side of the panel. They showed that these discontinuities are at different interpass locations. Therefore, compared to root pass discontinuities which are associated with the single root pass, the cap pass discontinuities are associated with one or more of the cap passes. Since the planned incomplete fusion defects were successfully implanted in the cap passes, this shows that the defect implantation techniques were highly controlled.

Metallographic and Fractographic Summary

The flaws seemed to generally propagate radially outwards and simultaneously along the complete perimeter. A unique initiation site could not be established. The initial flaw area was identified as a featureless surface whereas the extension of this flaw displayed a coarser fracture surface.

The welded explosion bulge test panels performed in one of two different ways depending on the flaw location. The two welds made with controlled root flaws resulted in propagation of these initial flaws through the thickness of the plate as well as along the weld length for a significant distance. The remaining four test panels had cap flaws, and in this case the propagation occurred mostly on the convex side. In contrast, the length of the final propagated flaw was only slightly extended for cap flaws (because of the single shot), and the propagation took place primarily towards the outer convex surface. The propagation of the initial flaw in all six panels was in the ductile mode as indicated by microvoids observed by SEM fractography.

Cross-sectional metallography confirmed that the initial flaws, especially the root flaws, were located in the controlled regions. In the case of the cap flaws, the indication was that in some regions, controlled flaws were not continuous but occupied different interpass locations along the width of the capping passes. Therefore, compared to root pass discontinuities which are associated with the single root pass, the cap pass discontinuities are associated with one or more of the cap passes. This appeared to be one of the primary reasons for the exposure of intermittent flaws in the fractures of the panels with cap pass discontinuities. Complete metallographic and fractographic results may be found in reference [11].

DISCUSSION

NDT/Metallography

The NDT results (Table 5) in comparison to the actual initial discontinuities showed that manual ultrasonic, enhanced radiographic and computer-aided ultrasonic correlated well. The computer results gave depth indications which also correlated well. The enhanced radiographic results (plus and minus 20° shot results analyzed together) perhaps correlated best with the actual fractographic results. It must be recalled however that either of the two radiographic results alone, or a normal shot, would not have displayed a probability of detection competitive with the UT because with one shot, in half the cases, the radiographs failed to indicate the entire length of the incomplete fusion. In summary though, the enhanced radiography technique utilized as we did here, is technically competitive with UT.

Table 5: Comparison of radiographic, manual ultrasonic and computer-aided ultrasonic initial discontinuity lengths.

Plate	Radiography (Enhanced)	Manual Ultrasonic	Computer-Aided Ultrasonic	Fractography
TM-1	67 mm	51 mm	38 mm	68 mm
TM-2 side 1	69 mm	51 mm	51 mm	65 mm
TM-2 side 2			51 mm	54 mm
TM-3 side 1	93 mm	51 mm	64 mm	90 mm
TM-3 side 2			64 mm	81 mm
TM-4	112 mm	102 mm	114 mm	117 mm
TM-5 side 1	70 mm	102 mm	102 mm	91 mm
TM-5 side 2			127 mm	59 mm
TM-6 side 1	84 mm	102 mm	127 mm	76 mm
TM-6 side 2			127 mm	106 mm

Explosion Bulge

The cap pass discontinuity plates showed less deformation because the tests were halted after one shot when the discontinuities broke to the surface (average strain of 12.3%). We halted the tests at this point to maximize our information on the flaw surface interaction. Our experience indicated that the plates would easily have withstood the additional strain to sixteen percent without failing the explosion bulge performance acceptance criteria. The root pass discontinuities were slower to reach the surface (2 shots with an average total strain of 17.0%).

New Criteria

There is an overriding observation here that may have escaped many people in the past. The propagation of discontinuities may not be a function of the discontinuity's size and location so much as the toughness and ductility of the adjacent weld metal and steel as defined by their structural transition performance. The lack of exaggeration of tearing associated with the various discontinuities in our study supports this and suggests that the discontinuity size and location acceptance criteria can be greatly relaxed when high quality weldment properties are maintained with advanced GMAW welding and controlled heat input and weldmetal cooling. Accordingly, we need to rethink acceptance criteria based on these observations.

In the future, focusing on nondestructive assessment of weldment properties in determining acceptance as opposed to just discontinuity sizing, could produce a dramatic improvement in confidence. The major weakness in an approach based on the relaxation of defect acceptance for weldments of improved structural transition is that one must be confident that processes, consumables and steels used consistently provide good structural transition performance. In our opinion the use of pulsed GMAW welding with C8 gas and more significantly TIME[1] gas and the new low weight digital welding systems [12] will provide this confidence and consistent performance.

As stated in the introduction, weld acceptance must be considered in the context not just of discontinuities (NDE) but weldment structural transition performance and fracture analysis. Tougher welds, prone to incomplete fusion, should not be evaluated with existing weld tradition. In the overall picture of things, brittle fracture of ships can only be eliminated by switching to higher grades of steel and welding that provides vastly improved structural transition performance. This change of fabrication will lead to relaxed discontinuity acceptance criteria. The added cost of better steel and improved welding (advanced GMAW welding may indeed be cheaper than current shipyard practice!), would be offset by lower costs due to relaxed NDE requirements.

CONCLUSIONS

1. Incomplete fusion can be detected reliably with enhanced radiography (two shot), and with manual and computer aided ultrasonics. Standard radiography (one normal shot) misses a significant proportion of the defects. Enhanced radiography performed the best.

2. Incomplete fusion defects can be produced in quality weldments without degrading the weld procedures and the surrounding weldmetal structural transition performance.

3. Defects in weldments in service above the structural transition temperature advance in a ductile mode. In our work, explosion test panels containing severe incomplete fusion defects performed well in explosion procedure trials. (Note: extreme undermatched welds would not pass).

4. Discontinuity size and location has less effect on propagation of discontinuities than previously thought when the weldment properties are not degraded in the process of producing the

discontinuities for study. This is true for defects significantly larger than those rejectable in standard weld acceptance standards.

5. Weld acceptance criteria should be based on whether the structural transition performance is below, within or above the operational envelope, (i.e. on structural transition performance of steel and welds as controlled by process, heat input and cooling) and not just location, size and type of discontinuities (i.e. factors that determine tearing versus brittle fracture).

6. Our approach demonstrates that the focus in weld examination should switch from mapping discontinuities to control of structural transition performance to support future weld acceptance criteria.

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